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The overall objective of this program is to determine the instantaneous flow structure on delta wings at high angle-of-attack, as well as from cylindrical bodies, which are subjected to basic classes of motion. New techniques of high-image-density particle image velocimetry provide the instantaneous vorticity fields and streamline patterns, thereby allowing interpretation of the underlying physics using critical point theory. This type of quantitative interpretation of the flow structure is crucial for performing vorticity balances on wings and bodies and thereby optimization of overall performance characteristics. Furthermore, for the case of the delta wing at high angle-of-attack, local control techniques are applied simultaneously at leading- and trailing-edges of the wing, in order to alter the crucial features of vortex breakdown and subsequent large-scale stall. Such control techniques have application to a wide variety of separated flows from wings and cylindrical bodies.

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FINAL TECHNICAL REPORT FOR AFOSR GRANT

UNSTEADY THREE-DIMENSIONAL AERODYNAMIC FLOW

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1. ABSTRACT

The overall objective of this program is to determine the instantaneous flow structure on delta wings at high angle-of-attack, as well as from cylindrical bodies, which are subjected to basic classes of motion. New techniques of high-image-density particle image velocimetry provide the instantaneous vorticity fields and streamline patterns, thereby allowing interpretation of the underlying physics using critical point theory. This type of quantitative interpretation of the flow structure is crucial for performing vorticity balances on wings and bodies and thereby optimization of overall performance characteristics. Furthermore, for the case of the delta wing at high angle-of-attack, local control techniques are applied simultaneously at leading- and trailing-edges of the wing, in order to alter the crucial features of vortex breakdown and subsequent large-scale stall. Such control techniques have application from a wide variety of separated flows to wings and cylindrical bodies.

2. EXPERIMENTAL SYSTEMS

During the course of this research program, a number of new experimental systems were developed. These systems are unique, in that they provide integrated control of a delta wing undergoing a maneuver, scanning illumination of the flow field past the wing, and acquisition of images of the flow. First of all, controlled motion of wings in both rolling and pitching modes, with deployable leading-edge flaps and trailing-edge blowing (for the pitching mode) have been developed and instrumented. These systems are controlled with high resolution, computer-based stepping motors that, in turn, are synchronized with the image illumination and acquisition systems. Illumination is obtained by high-speed scanning of an Argon-ion laser across the field of interest, using one of several Argon systems. The scanning is achieved by a rotating mirror assembly, having seventy-two facets, providing an effective scan rate of the laser beam having a value orders of magnitude higher than the time scale of the flow and its interaction with the wing. Acquisition of images is achieved using a motor-driven 35 mm camera at framing rates up to ten frames per second to preclude directional ambiguity of the flow and image shifting mirrors employed immediately ahead. Finally, interrogation of the acquired patterns of particle images provides the instantaneous velocity distribution over entire planes of the flow. From these distributions, the corresponding patterns of vorticity and streamlines can be calculated. An important theoretical link is the use of critical point

theory to interpret the streamline topology, in conjunction with the instantaneous patterns of vorticity. This approach provides a rational, quantitative-based method of interpreting complex, unsteady flows on wings at high angle-of-attack.

3. ACCOMPLISHMENTS/NEW FINDINGS

Several parallel investigations have allowed new insight into the unsteady structure of flows on delta wings at high angle of attack subjected to various types of control during their motion. In the following, each advance is described in the context of the corresponding journal article. Each article provides complete details on the experimental system and techniques and, of course, the principal findings. In all cases, the lead author is a graduate student; the journal article therefore represents a synopsis of the major advances, which are described in detail in the full thesis available from the Department of Mechanical Engineering and Mechanics at Lehigh University.

3.1 *CROSSFLOW TOPOLOGY OF FLOW STRUCTURE ON A DELTA WING: EFFECT OF SELF-EXCITED EXCURSIONS OF VORTEX BREAKDOWN (K. M. Cipolla and D. Rockwell, 1996, AIAA Journal of Aircraft (submitted))*

Vortex breakdown of a delta wing at high angle-of-attack exhibits large amplitude, self-excited excursions of the vortex breakdown location. Although these self-excited excursions exhibit a time scale that falls within a relatively narrow band of frequencies, they are not perfectly periodic. The instantaneous position of vortex breakdown was monitored using a dye injection technique and, simultaneously, the particle image velocimetry technique was used to determine the instantaneous velocity distribution, and therefore the instantaneous distributions of vorticity and velocity in the crossflow plane. It is demonstrated that the axial excursions of vortex breakdown are accompanied by changes in the fundamental topology, depending upon the location of the crossflow plane relative to the onset of vortex breakdown. The existence of stable and unstable foci (inward versus outward spiral of the streamline pattern) has been linked to the variation of the vortex breakdown position and the degree of concentration of the instantaneous vorticity over the crossflow plane.

3.2 *QUANTITATIVE IMAGING AND PROPER ORTHOGONAL DECOMPOSITION OF FLOW PAST A DELTA WING (K. M. Cipolla, A. Liakopoulos, and D. Rockwell, AIAA Journal (submitted)).*

Although the technique of proper orthogonal decomposition has been employed extensively in traditional turbulent flows, such as boundary layers and free shear layers, this investigation represents the first application of POD to the complex, unsteady flow past a delta wing at a high angle-of-attack. In particular, a snapshot version of the POD technique, which employs a large number of successive images of the crossflow velocity or vorticity pattern, or, a sectional cut parallel to the surface of the wing of the velocity field and vorticity pattern, provides the essential information for implementation of this approach. It is demonstrated that the principal features of the leading-edge vortex of the delta wing, in both its coherent and broken-down states, can be described with a very small number of images representative of the most energetic modes of the flow pattern.

3.3 *MULTIPLE-ACTUATOR CONTROL OF VORTEX BREAKDOWN ON A PITCHING DELTA WING (P. Vorobieff and D. Rockwell, AIAA Journal, Vol. 34, No. 10, pp. 2184-2186)*

During the pitching maneuver of a delta wing to a high angle-of-attack, leading-edge flaps and trailing-edge blowing have been implemented, in order to retard the onset of vortex breakdown, relative to that which occurs for the case of no local control techniques at the leading- and trailing-edges of the wing. A particularly important finding of this program is that transient blowing, applied only over a portion of the pitching cycle of the wing, is very effective in retarding the onset of vortex breakdown. In fact, the phase lag of the controlled vortex breakdown persists into that portion of the wing oscillation cycle for which the control is not applied. It is this phase lag that allows very low values of effective blowing coefficient to be employed for effective control.

3.4 *WAVELET FILTERING FOR TOPOLOGICAL DECOMPOSITION OF FLOW FIELDS (P. Vorobieff and D. Rockwell, 1996, International Journal of Imaging Systems and Technology*, Vol. 7, pp. 211-214)

It is envisioned that control sensors for maneuver of delta wings will eventually employ not simply pointwise measurements of pressure or other local parameter on the surface of the wing, but a global indication of the overall pattern of the flow past the wing. For example, a vapor screen or laser sheet could be created and patterns of the crossflow topology of the leading-edge vortex identified as input for the control technique. If this approach is to be successful, then it will be necessary to have a rapid means of identifying the key features of the flow pattern, most importantly the onset of vortex breakdown. A wavelet transform technique has been developed, with a mother wavelet that very efficiently recognizes the principal features of the streamline topology in the vicinity of vortex breakdown. This type of wavelet approach is expected to allow identification of a number of key critical points in complex aerodynamic flows.

3.5 *FLOW STRUCTURE ON A STALLED DELTA WING SUBJECTED TO SMALL-AMPLITUDE PITCHING MOTIONS (K. M. Cipolla and D. Rockwell, 1995, AIAA Journal, Vol. 33, No. 7, pp. 1256-1262)*

Pitching of a delta wing at high angle-of-attack induces regions of large-scale stall. The development of these stall regions is substantially retarded in phase relative to the pitching motion of the wing. This investigation provides instantaneous, quantitative insight into these stall regions and their development, using patterns of vorticity and streamline patterns, interpreted with the aid of critical point theory. Identification of the large-scale vortical motion is accomplished by defining saddle points and stable and unstable foci of the large scale patterns.

3.6 *FLOW STRUCTURE ON A DELTA WING: INSTANTANEOUS VORTICITY FLUX IN CROSSFLOW PLANE (with K. M. Cipolla and D. Rockwell, 1997, submitted to AIAA Journal)*

Contrary to the traditional interpretation of a leading-edge vortex on a delta wing, it does not form from an undisturbed vorticity sheet emanating from the leading-edge of the

wing. Rather, small-scale concentrations of vorticity, each having a circulation approximately one order of magnitude smaller than the circulation of the leading-edge vortex, but together having a circulation that is the same order as the major leading-edge vortex, have been observed in these aerodynamic flows at high angle-of-attack. This investigation provides the first definition of the small-scale concentrations of vorticity to form in two kinds of separated shear layers. The first is due to separation from the leading-edge and the second due to separation from the leeward surface of the delta wing. In fact, the small-scale concentrations of vorticity, which are of the Kelvin-Helmholtz type, evolve in a coupled fashion much like a wake-type flow observed in two-dimensional configurations. This observation is important, since it shows the mechanism by which the well-known, primary vortices developed on a delta wing at high angle-of-attack.

3.7 *TRANSIENT STRUCTURE OF VORTEX BREAKDOWN ON A DELTA WING AT HIGH ANGLE-OF-ATTACK (J.-C. Lin and D. Rockwell, 1995, AIAA Journal, Vol. 33, No. 1, pp. 6-12)*

A delta wing is subjected to a transient ramp-like motion to high angle-of-attack and the unsteady development of the vortex breakdown is observed. Radical transformations in the structure of the leading-edge vortex are observed over a cross-sectional cut through the centerline of the leading-edge vortex. The azimuthal vorticity is relatively distributed prior to the onset of vortex breakdown. After breakdown occurs, the orientation of the positive and negative contours of azimuthal vorticity abruptly switch and take the form of pronounced concentrations, characteristic of the helical mode of instability. Moreover, a number of other key features of the streamline topology and patterns of vorticity are revealed, which are unexpected based on quasi-steady considerations.

3.8 *THREE-DIMENSIONAL PATTERNS OF STREAMWISE VORTICITY IN THE TURBULENT NEAR-WAKE OF A CYLINDER (J.-C. Lin, P. Vorobieff, and D. Rockwell, 1995, Journal of Fluids and Structures, Vol. 9, pp. 231-234)*

The existence of unsteady concentrations of streamwise vorticity occurs in both delta wing configurations and in cylindrical bodies subjected to crossflow. This investigation focused on an occasion of the highly-coherent and persistent nature of these patterns of streamwise vorticity in a turbulent near-wake. Using a space-time imaging technique, contours of iso-vorticity have been constructed in three-dimensional space. This approach provided the first quantitative representation of patterns of vorticity in a grossly-separated flow using the technique of high-image-density particle image velocimetry.

3.9 *SPACE-TIME IMAGING OF A TURBULENT NEAR-WAKE BY HIGH-IMAGE-DENSITY PARTICLE IMAGE CINEMATOGRAPHY, J.-C. Lin, P. Vorobieff and D. Rockwell, 1996 Physics of Fluids, Vol. 8, No. 2, pp. 555-564)*

Quantitative evaluation of the instantaneous circulation of the possible modes of streamwise vorticity, for the case of a turbulent near-wake of a cylinder, has been undertaken using the technique of space-time imaging. Using a high-speed cinema camera, the instantaneous concentrations of vorticity were determined over a crossflow plane at successive instants of time. Both sectional and space-time imaging allowed

interpretation of the concentrations of streamwise vorticity relative to the much studied, qualitative visualization of the near-wake of a circular cylinder at low Reynolds number.

3.10 *ORBITAL OSCILLATIONS OF A CYLINDER IN PRESENCE OF A FREE-SURFACE: VORTEX FORMATION AND LOADING, O. Cetiner, Q. Zhu, J.-C. Lin, M. F. Unal, and D. Rockwell, 1996, Bulletin of the American Physical Society, Vol. 41, No. 9, Abstract No. HD4, p. 1810.*

A circular cylinder is subjected to an orbital motion in both a quiescent fluid and in a steady stream. Instantaneous velocity fields, streamline patterns and distributions of vorticity concentrations are identified. Preliminary application of vorticity moment concept, that allows calculation of the instantaneous lift and drag on the cylinder, in relation to the primary concentrations of vorticity, has been undertaken, and will form a basis for further studies in this direction.

4. PERSONNEL SUPPORTED

Kimberly Cipolla Ph.D. Degree (1996)
Peter Vorobieff, Ph.D. Degree (1996)
Oksan Cetiner, Ph.D. Candidate (expected date of degree completion - June, 1998)
Jung-Chang Lin, Research Associate

5. PUBLICATIONS (all of the following publications were supported either in whole or in part by this AFOSR grant)

Journal Articles

Cipolla, K. M. and Rockwell, D. 1997 "Flow Structure on a Delta Wing: Instantaneous Vorticity Flux in Crossflow Plane", to be submitted to *AIAA Journal.*

Vorobieff, P. and Rockwell, D. 1997 "Control of Vortex Breakdown on a Pitching Half-Delta Wing by Intermittent Trailing-Edge Blowing" to be submitted to *AIAA Journal.*

Canbazoglu, S., Lin, J.-C., Wolfe, S. and Rockwell, D. 1996 "Buffeting of a Fin: Streamwise Evolution of Flow Structure", *AIAA Journal of Aircraft*, Vol. 33, #1, pp. 185-190.

Cipolla, K. M., Liakapoulos, A, and Rockwell, D. 1996 "Quantitative Imaging in Proper Orthogonal Decomposition of Flow Past a Delta Wing", submitted to *AIAA Journal.*

Cipolla, K. M. and Rockwell, D. 1996 "Crossflow Topology of Flow Structure on a Delta Wing: Effect of Self-Excited Excursions of Vortex Breakdown", submitted to *AIAA Journal of Aircraft.*

Jefferies, R. and Rockwell, D. 1996 "Interaction of a Vortex with an Oscillating Leading-Edge", *AIAA Journal*, Vol. 34, No. 11, pp.2448-2450.

Lin, J.-C., Vorobieff, P. and Rockwell, D. 1996 "Space-Time Imaging of a Turbulent Near-Wake by High-Image-Density Particle Image Cinematography", *Physics of Fluids*, Vol. 8, No. 2, pp. 555-564.

Vorobieff, P. and Rockwell, D. 1996 "Multiple-Actuator Control of Vortex Breakdown on a Pitching Delta Wing", *AIAA Journal*, Vol. 34, No. 10, pp. 2184-2186.

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Canbazoglu, S., Lin, J.-C. Wolfe, S. and Rockwell, D. 1995 "Buffeting of Fin: Distortion of Incident Vortex", *AIAA Journal*, Vol. 33, No. 11, pp. 2144-2150.

Cipolla, K. and Rockwell, D. 1995 "Flow Structure on a Stalled Delta Wing Subjected to Small-Amplitude Pitching Motions", *AIAA Journal*, Vol. 33, No. 7, pp. 1256-1262.

Lin, J.-C. and Rockwell, D. 1995 "Transient Structure of Vortex Breakdown on a Delta Wing at High Angle-of-Attack", *AIAA Journal*, Vol. 33, No. 1, pp. 6-12.

Lin, J.-C. and Rockwell, D. 1995 "Transient Structure of Vortex Breakdown on a Delta Wing at High Angle-of-Attack", *AIAA Journal*, Vol. 33, No. 1, pp. 6-12.

Lin, J.-C., Vorobieff, P. and Rockwell, D. 1995 "Three-Dimensional Patterns of Streamwise Vorticity in the Turbulent Near-Wake of a Cylinder", *Journal of Fluids and Structures*, Vol. 9, pp. 231-234.

Wolfe, S., Canbazoglu, S., Lin, J.-C. and Rockwell, D. 1995 "Buffeting of Fins: An Assessment of Surface Pressure Loading", *AIAA Journal*, Vol. 33, No. 11, pp. 2232-2235.

Wolfe, S., Lin, J.-C. and Rockwell, D. 1995 "Buffeting of the Leading-Edge of a Flat Plate due to a Streamwise Vortex: Flow Structure and Surface Pressure Loading", *Journal of Fluids and Structures*, Vol. 9, pp. 359-370.

Mayori, A. and Rockwell, D. 1994 "Interaction of a Streamwise Vortex with a Thin Plate: A Source of Turbulent Buffeting", *AIAA Journal*, Vol. 32, No. 10, pp. 2022-2029.

Abstracts (APS, 1996)

Cetiner, O, Zhu, Q., Lin, J.-C., Unal, M. F. and Rockwell, D. 1996 “Orbital Oscillations of a Cylinder in Presence of a Free-Surface: Vortex Formation and Loading”, *Bulletin of the American Physical Society*, Vol. 41, No. 9, Abstract No. HD4, p. 1810

Cipolla, K. M., Liakopoulos, A. and Rockwell, D. 1996 "Quantitative Imaging in Proper Orthogonal Decomposition of Flow Past a Delta Wing", *Bulletin of the American Physical Society*, Vol. 41, No. 9, Abstract No. IE3, p. 1826.